Effect of Microalloying on Structure and Properties of Hot Rolled 0.5 %C Steel

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Abstract

The influence of adding molybdenum and niobium on the microstructure and mechanical properties of C5 steel used in railway wheels was studied. The samples were heated to 1250°C and hot rolled in four passes, starting at 1200°C, undergoing a total reduction of 67%, followed by air cooling. After rolling between 1200 and 1120°C, it was found that addition of molybdenum and niobium resulted in an increase of mechanical strength while maintaining the same ductility and toughness.

Keywords

Railway Wheels; Carbon Steel; Molybdenum; Niobium

Introduction

The traditional railway wheels are manufactured with medium and high carbon steels, depending on the type of application. The standard AAR [1] (Association of American Railroads) only requires hardness measurement of 25 mm from the tread on the front face of the rim (Table 1). Fig. 1 shows parts of a railway wheel.

The railroads are demanding for the companies that produce wheels made by a material with higher hardness and hardenability without changes in carbon amount, that´s why this work was developed.

TABLE 1 CLASSES OF RAILWAY WHEELS[1]

Class	Carbon (%)	Hardness (BHN)	Applications
L	0.47 max.	197 - 277	High-speed service, severe braking conditions and light wheel loads.
A	0.47 – 0.57	255 - 321	High-speed service, severe braking conditions with moderate wheel loads.
B	0.57 – 0.67	302 - 341	High-speed service with severe braking conditions and heavier wheel loads.
C	0.67 – 0.77	321 - 363	Slow-speed service, light braking conditions and heavy wheel loads.

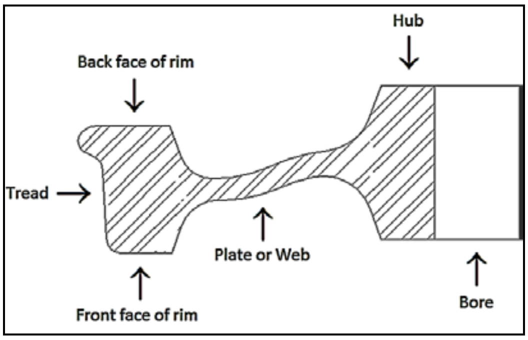


FIG. 1 PARTS OF A RAILROAD WHEEL [2]

Niobium is added at levels lower than 0.05% in steel to promote austenite grain refinement and precipitation hardening [3, 4]. Carbon-manganese microalloyed steels with niobium has been used to produce structures of high strength with good toughness and weldability [5, 6].

Mei [7] showed that for a rolling process in two passes, with 34% reduction in medium-carbon steels (0.4% C), the addition of 0.03% Nb reduced austenite grain size and increased yield and tensile strengths, without significant changes in ductility. These effects were more pronounced as the rolling temperature was increased, since it produced a greater fraction of niobium dissolved in austenite. The addition of niobium was also responsible for the reduction of pearlite interlamellar spacing, with a greater effect by using the rolling temperature of 1250°C. This was due to niobium delaying initial temperature of pearlite formation, which results in the formation of thinner pearlite thus increasing its hardness.

García de Andrés et al. [8] studied the influence of molybdenum on the microstructure of medium carbon forged steel (0.38% C) under various conditions of cooling. The transformation austenite - acicular ferrite in the steel without molybdenum occurs from 25 to 1°C/sec. In steel with 0.16% Mo, the transformation occurred from 30 to 0.5°C/sec, i.e., the transformation region was expanded to lower cooling rates and the

initial temperatures of acicular ferrite formation were slightly higher. It was observed that the addition of molybdenum in steel favored the formation of acicular ferrite.

Materials and Methods

Preparation of Experimental Steels

The alloys used in this work were produced by Villares Metals in an induction furnace under vacuum conditions. Ingots with average cross-section of 140 mm² were shaped by forging process to 90 mm² at temperatures from 1180°C to 1200°C. The chemical composition of the alloys produced is shown in Table 2.

TABLE 2 CHEMICAL COMPOSITIONS OF STEELS (wt%)

Steel grade	C	Si	Mn	P	S	Cr	Mo+Nb	Al
C5	0.521	0.319	0.639	0.015	0.015	0.134	0.039	0.019
C5Nb	0.487	0.313	0.670	0.017	0.008	0.218	0.200	0.018

Specimens for Rolling Testing

Specimens of both non-microalloyed C5 steel and microalloyed C5Nb steel were prepared as per drawing shown in Fig. 2 for hot rolling. The two specimens were coupled by a pin with diameter of 9,52 mm. This was performed in order to ensure that the two specimens had an identical sequence of rolling, i.e., the only existing variable would be the chemical composition of steels. Chamfers were made in order to facilitate entry between the rolling rolls and two 3 mm holes in each specimen K-type thermocouples, one for each type of steel.

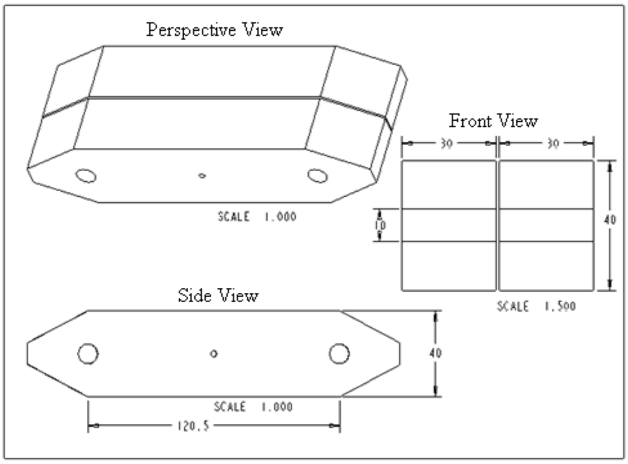


FIG.2 SKETCH OF SPECIMEN FOR ROLLING (mm)

To simulate forging in the actual manufacturing process, the rolling specimens were heated by a muffle furnace at 1250°C for 30 minutes to ensure dissolution of niobium. Afterwards, they were rolled, on a laboratory scale Duo-reversible rolling, model FENN-051 50 ton capacity, in 4 passes, starting at 1200°C and undergoing a total deformation (reduction in height) of 67% until 1126°C, followed by air cooling at the rate of 3°C/sec. A recorder was also used to monitor the material's temperature through thermocouple during the thermomechanical treatment. Rolling parameters are given in Table 3.

TABLE 3 HOT ROLLING PARAMETERS

Pass Number	Initial thickness (mm)	Final thickness (mm)	Reduction/pass		Pass temperature (°C)
			(%)	(mm)	
1	40.0	31.5	21	8.5	1200
2	31.5	23.1	21	8.5	1179
3	23.1	16.7	16	6.4	1152
4	16.7	13.0	9	3.7	1126

Metallographic Analysis

The metallographic analysis was performed at the Laboratory of the Department of Materials Engineering (DEMA), Unicamp, on samples before and after rolling, in the transverse direction. The samples were prepared according to the standard procedures and etched with Nital 2% solution. After etching, samples were analyzed under optical microscope Neophot 32 and scanning electron microscope Jeol JXA-840. The volume fraction of ferrite was measured using a Leica image analyzer. There were 5 measurements for each sample. To obtain the average value of minimum interlamellar spacing, S_{0min}, 10 regions that had the thinnest lamellae of pearlite were measured for each sample. Additionally, it was possible, through measurement on the computer screen, to count how many lamellae of cementite were intercepted in a standard line of 30 mm.

Cylindrical samples were prepared for the purpose of partial quenching. The samples were reheated to austenitizing temperature of 900°C for 20 minutes and were partially immersed in water. Mechanical tests were performed at room temperature, with aim to correlate austenite grain size with mechanical properties. The steel was heated to a temperature of 900°C to prevent rapid grain growth, which occurs at 1000°C [9]. The samples were immersed for 5 minutes in a solution of 6 g of picric acid + 300 ml H_2O + 15 ml of sodium sulfonate to reveal the prior austenite grain boundary. Measurements of grain size were obtained

by the method of linear intercepts in 10 different regions.

Mechanical Testing

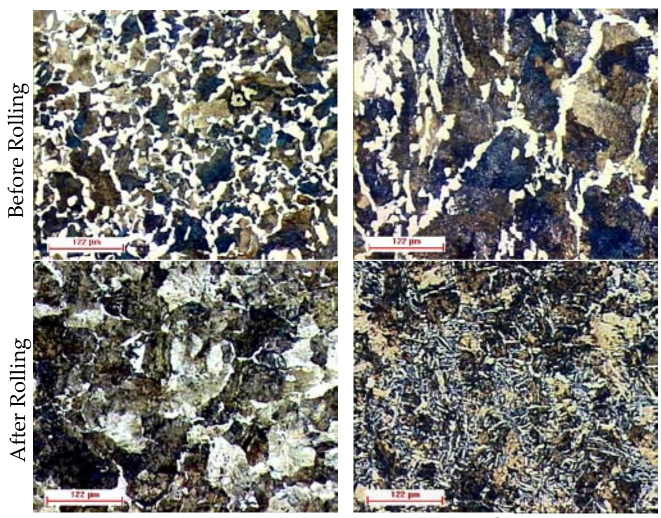
The hardness tests were carried out on MWL Brazil - Wheels and Axles Ltd according to ASTM A370 [10]. The tests were performed on Brinell hardness tester Wilson - 3000 kg Microhardness tester LEITZ – WETZLAR was used for ferrite and pearlite grains.

The tensile test was conducted at MTS machine at room temperature according to ASTM-370 [10], in 2 samples before and after rolling. The specimens were collected in the rolling direction.

Impact tests were performed on MWL Brazil - Wheels and Axles Ltd in accordance with ASTM E 23 [11], using an impact pendulum LOS, PSW model, and maximum load capacity of 294 J. Impact tests were performed at -40, 25 and 300°C for steels after rolling and only at room temperature for steels after rolling, quenching and tempering. Temperatures -40, 25 and 300°C were used in order to, respectively, simulate the use of railroad wheels in cold places, at room temperature and under severe braking, where the surface temperature of the wheel may reach 300°C [1].

Results and Discussion

Before rolling, the non-microalloyed steel presented a more homogeneous microstructure (Fig. 3) with a higher volume fraction of ferrite than that of microalloyed steel as evident from Fig. 4, and the ferrite located at the prior austenite grain boundaries.



(a) (b)

FIG . 3 OPTICAL MICROGRAPHS OF THE STEELS BEFORE AND AFTER ROLLING: (a) C5, (b) C5Nb. NITAL 2%

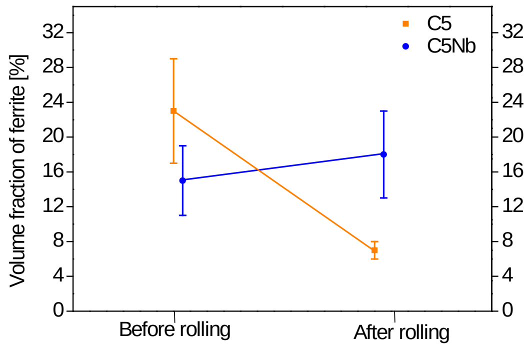
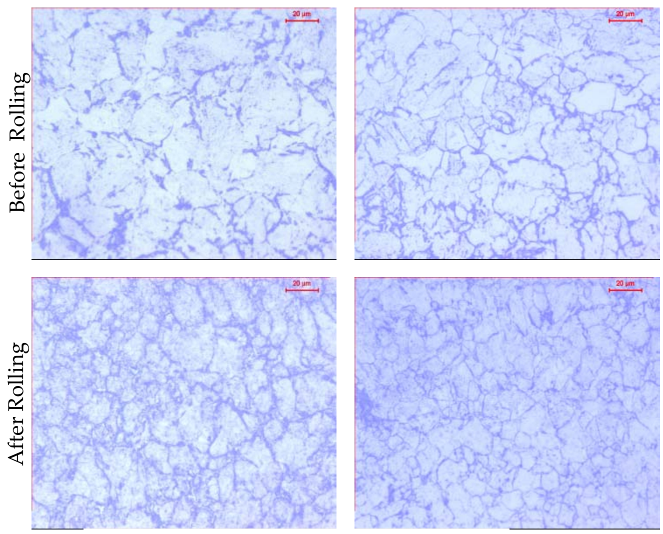


FIG. 4 VOLUME FRACTION OF FERRITE(%) OF STEELS BEFORE AND AFTER ROLLING

After rolling, the non-microalloyed steel presented a significant reduction in the ferrite fraction that might have been caused by a higher cooling rate, which favored the reduction of volume fraction of ferrite [9]. The opposite occurred in microalloyed steel, i.e., there was a slight increase in volume fraction of ferrite, but with one significant difference that before rolling ferrite had an equiaxial structure formed at the prior austenite grain boundary and after rolling, the ferrite was acicular and distributed throughout the sample, probably due to the addition of molybdenum, which facilitates the acicular ferrite formation [12].

Fig. 5 shows the prior austenite grain boundary of steels before and after rolling. The microalloying promoted a refinement of austenite grain with a greater effect on steels (Fig. 6). It is known that niobium has a strong tendency to form carbides that restrict the growth of the austenite grain [7, 13].



(a) (b)

FIG. 5 AUSTENITE GRAIN SIZE BEFORE AND AFTER ROLLING: (a) C5, (b) C5Nb. ETCHANT: 6g PICRIC ACID + 300 ml H_2O + 15 ml SODIUM SULFONATE

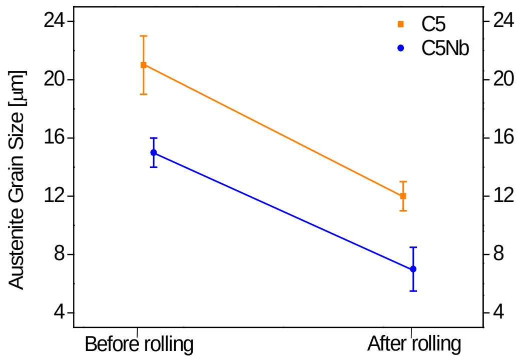


FIG. 6 AUSTENITE GRAIN SIZE BEFORE AND AFTER ROLLING

Fig. 7 shows the pearlitic structure of the C5 and C5Nb steels before and after rolling and a greater tendency of pearlite degeneration was noticed in C5Nb steel.

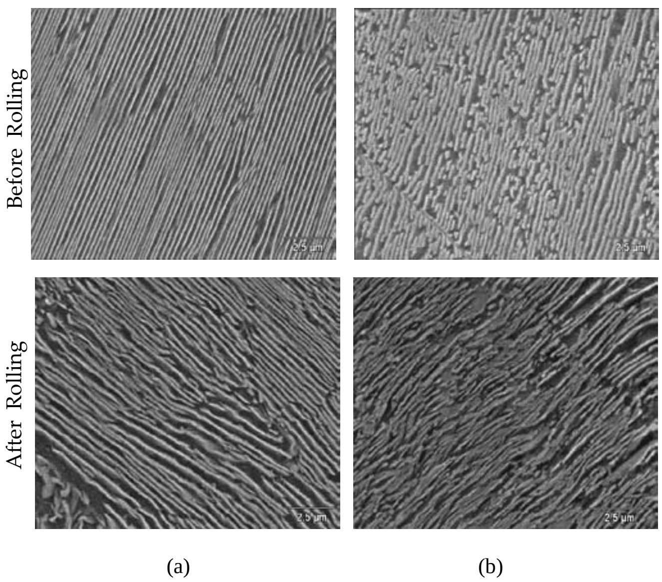


FIG. 7 PEARLITIC MICROSTRUCTURE BEFORE AND AFTER ROLLING: (a) C5, (b) C5Nb. NITAL 2%

After rolling, the interlamellar spacing value ranged in opposite ways and for different reasons for steels with and without microalloying (Fig. 8). In non-microalloyed steels, rolling caused a reduction in volume fraction of ferrite, due to the higher cooling rate at which the steel was exposed in relation to the previous condition: forged and air-cooled. This ferrite reduction led to "dilution" of pearlite [9], which probably explains the increase in pearlite interlamellar spacing. Metallurgically a dilution of the pearlite can be achieved by increasing the cooling rate in the transformation range or by increasing the alloying content; for this Mn is particularly efficient. Both these amendments will give rise to increased pearlite content, and therefore at constant carbon content the pearlite will be more diluted of cementite [14].

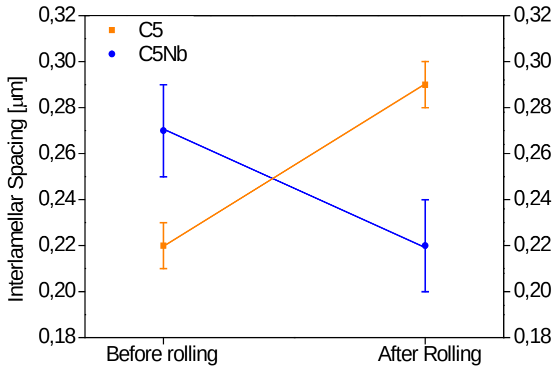


FIG. 8 PEARLITE MINIMUM INTERLAMELLAR SPACING BEFORE AND AFTER ROLLING

In microalloyed steel, heating prior to rolling at 1250°C solubilized most of the niobium, which led to a reduction of 60°C at the initial temperature of pearlite formation [14], detected by thermocouples (Fig. 9). The decrease in the initial temperature of pearlite formation reduced the pearlite interlamellar spacing. In this case, as there was not a significant change in volume fraction of ferrite, the pearlite was not diluted. Molybdenum also contributes to delaying the formation of ferrite and pearlite.

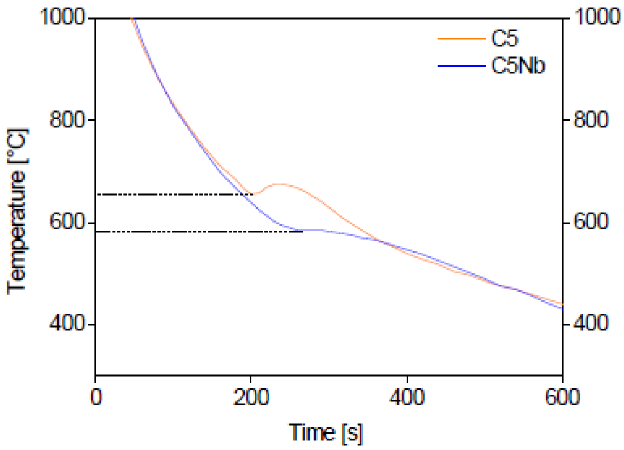


FIG. 9 INITIAL TEMPERATURE OF PEARLITE FORMATION

Fig. 10 and Tab. 4 indicate that the rolling has slightly increased (11 HB or 10 HV) the C5 steel hardness. This can be explained by the reduction in the volume fraction of ferrite from 23% to 7%, considering that the pearlite is the harder phase and that there was practically no change in its hardness, taking into account the wide dispersion observed in the measurements (Tab. 4).

TABLE 4 MACROHARDNESS AND PEARLITE AND FERRITE MICROHARDNESS OF C5 AND C5Nb STEELS

	Steel Grade	Before rolling	After rolling
Hardness HB (HV)	C5	222 ± 13 (235)	233 ± 9 (245)
	C5Nb	206 ± 2 (217)	249 ± 10 (262)
Pearlite Hardness (HV)	C5	245 ± 18	256 ± 30
	C5Nb	259 ± 7	275 ± 10
Ferrite Hardness (HV)	C5	195 ± 13	ND*
	C5Nb	204 ± 10	ND*

ND* = It was not possible to measure the hardness, since the area of ferrite was very small.

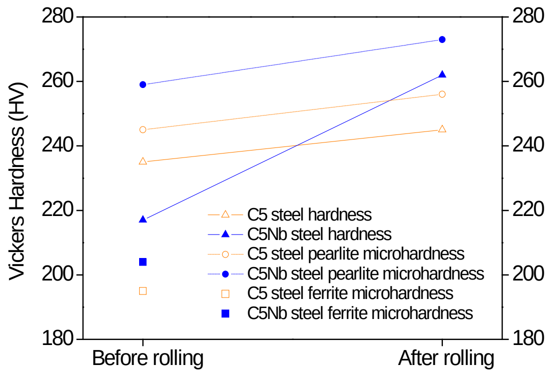


FIG. 10 HARDNESS RESULTS OF THE C5 AND C5Nb STEELS

In microalloyed steel, rolling greatly increased its hardness (43 HB or 45 HV), due to the increase in pearlite hardness (14 HV or 6%), because there was a slight change in the volume fraction (from 15% to 18%). The increased hardness of the C5Nb steel pearlite was due to the reduction of pearlite interlamellar spacing (from 0.27 to 0.22μm). However, other factors could also be acting, such as niobium carbide precipitation, in the ferrite of pearlite, and in pearlite degeneration [10]. The ferrite hardness of untreated C5Nb steel was slightly higher (10 HV) than that of C5 steel, which may be due to niobium carbide precipitates. It was also observed that before rolling the hardness of C5 steel had a slightly higher (16 HB or 18HV) than that of C5Nb, which is consistent with its smaller pearlite interlamellar spacing compared to C5Nb steel i.e., 0.22 and 0.27μm, respectively.

Figure 11 presents the tensile test results before and after rolling. In the unrolled steel, the combined application of niobium and molybdenum changed little the mechanical strength but improved ductility, which increased the elongation from 19% to 23% and increased the reduction in area from 37 to 46%. After rolling, the microalloyed steel showed an increase of 170 MPa in yield strength, with insignificant change in ductility. The reduction of the interlamellar spacing of pearlite justifies the increase of the yield strength in the C5Nb microalloyed steel [16, 17].

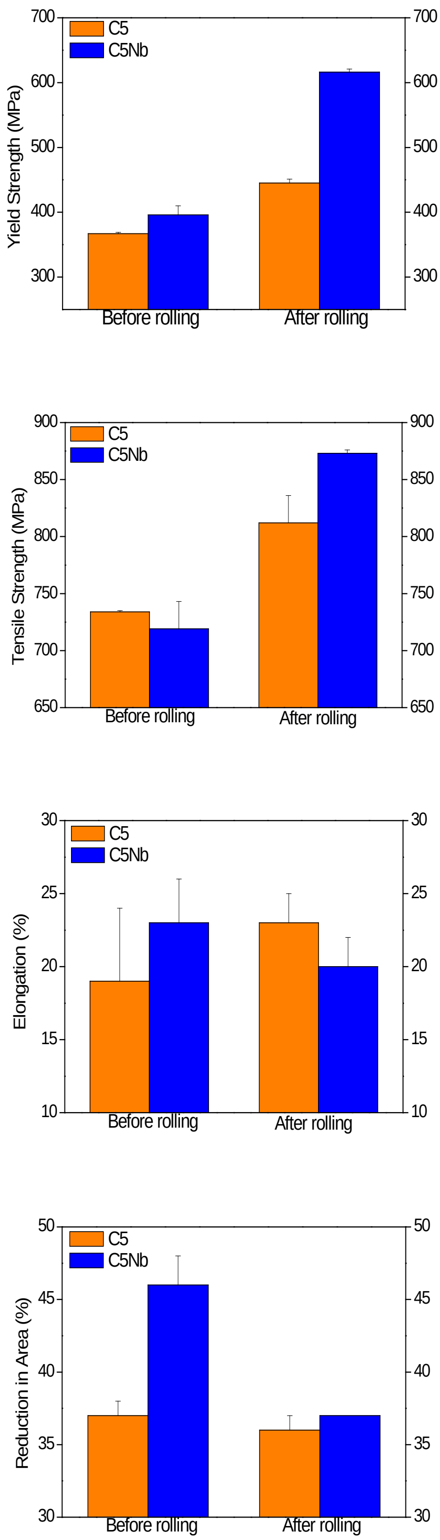


FIG. 11 TENSILE TEST RESULTS OF C5 AND C5Nb STEELS BEFORE AND AFTER ROLLING

It is found that rolling increases the mechanical strength of steels, with and without addition of Nb and Mo. However it did not affect the ductility, measured by elongation and area reduction, of non-microalloyed steels, whereas this characteristic was reduced in microalloyed steels. The impact test failed to demonstrate a reduction in toughness of microalloyed steel at temperatures between -40 and 300° C (Table 5).

TABLE 5 IMPACT ABSORBED ENERGY(J) OF C5 AND C5Nb ROLLED STEELS

Steel Grade	Test temperature (°C)		
	-40	25	300
C5	4 ± 1	6 ± 1	60 ± 5
C5Nb	5 ± 1	11 ± 1	62 ± 2

Conclusions

The hot rolling of small steel samples in the laboratory successfully simulated the actual process of railway bogie wheels manufactured at MWL Brazil Company.

Comparing the steels with and without addition of molybdenum and niobium after hot rolling between 1200 and 1120°C with 67% total reduction in thickness, it was observed that the addition of Mo and Nb provided an increase of mechanical strength, maintaining the ductility and toughness.

The molybdenum addition favored the formation of acicular ferrite.

The increase in mechanical strength was caused by the following factors: reduction in the initial temperature of pearlite formation to 60°C, reduction in the interlamellar spacing of pearlite and refining the austenite grain size.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from MWL Brazil Company - Wheels and Axles Ltda. and FAPEMA – Maranhão State Research Foundation.

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